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Concepts and New Implements for Modified Physiologically Equivalent Temperature

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Abstract: Different kinds of thermal indices have been applied in several decades as essential tools to investigate thermal perception, environmentally thermal conditions, occupant thermal risk, public health, tourist attractiveness, and urban climate. Physiologically equivalent temperature (PET) has been proved as a relatively wide applicable thermal indicator above other thermal indices. However, the current practical PET performs a slight variation influenced by changing the humidity and clothing insulation. The improvement of the PET has potentiality for further multi-application as a general and consistent standard to estimate thermal perception and tolerance for different studies. To achieve the above purpose, modified physiologically equivalent temperature (mPET) is proposed as an appropriate indicator according to the new structure and requirements of the thermally environmental ergonomics. The modifications to formulate the mPET are considerably interpreted in the principle of the heat transfer inside body, thermo-physiological model, clothing model, and human-environmental interaction in this study. Specifically, the mPET-model has adopted a semi-steady-state approach to calculate an equivalent temperature refer to an indoor condition as the mPET. Finally, the sensitivity test of the biometeorological variables and clothing impact proves that the mPET has better performance on the humidity and clothing insulation than the original PET.

Keywords: thermal indicator; thermal condition; thermal perception; physiologically equivalent temperature (PET); modified physiologically equivalent temperature (mPET); environmental ergonomics

1. Introduction

As a thermal index, the physiologically equivalent temperature (PET) [1,2] is one of the outstandingly and applicably rational indicators [3]. Thermal indices were developed initially in empirical formulas to give a comprehensive evaluation of thermally environmental impacts on the human beings [4–6]. While the evaluation of the environmental impacts is only focused, several previous studies pointed out that PET is not appropriate to be applied in high humid conditions on the estimation of humidity factors [7–9]. Concurrently, based on the same perspective, there are also other rationally thermal indicators besides PET, such as Predicted Mean Vote (PMV) [10,11], rational Standard Effect Temperature (SET*) [12–14], Universal Thermal Climate Index (UTCI) [15–18], and Perceived Temperature (PT) [19,20]. Each above-mentioned indicator has some application restrictions. Otherwise, some empirical indicators have been kept applied in public health fields. A common one of these empirical indicators—Wet Bulb Globe Temperature (WBGT) [21]—is still applied to predict fatal heat stress in the public health field [22–24].

Each thermal indicator has appropriate applicability and peculiar development background. PMV has been proposed as the first rational thermal indicator which can consider the heat transfer from body core to body shell, then to clothing node, and finally to the environments. This thermo-physiological model is known as a two-nodes cylinder body model [10,11]. Moreover, PMV applies a conserve-energy approach to carry out an equilibrium state. Applying the equilibrium state to refer a thermally comfortable standard environment, a rank of thermal strains would be carried out as an estimation of the surrounding thermal conditions. However, PMV has been initially proposed to consider the thermal conditions inside buildings and not effectively sensitive to the radiant impacts [25]. Another inadequacy of PMV is that the clothing insulation is fixed in 0.6 clo for summer specific cases [26]. SET* has been proposed also based on a two node body cylinder model but to solve standardization of metabolism and clothing behavior. Therefore, the computational model of SET* is a time-dependent thermo-physiological model and not entirely based on human energy equilibrium. The performances of SET* are violently sensitive to wind speed in cold conditions and slightly sensitive to mean radiant temperature (T_{mrt}) in warm conditions. Another peculiarity of SET* is adjustment of subject's clothing behavior with metabolic rate as a standardization. This mechanism causes that SET* varies violently due to the changing of metabolic rate or clothing insulation. Afterwards, PET which is also based on human energy-balance model has extraordinarily improved the sensitivity on radiant impacts and also kept performance on air temperature (T_a) and wind velocity (v). However, sensitivity of PET on humidity is inconspicuous. Subsequently, PT has appended winter clothing insulation as 1.2 clo to complement clothing model of PMV and transfer the thermal level of PMV to an equivalent temperature. Concurrently, UTCI has been based on a improved thermo-regulatory model which has enhanced a two-nodes cylinder body model to a 304 nodes multiple-segments body model and a air-temperature-depending clothing parameter deduced by multiple-layer clothing model. However, UTCI is given actually by a regression optional function which is carried out by meteorological data sets and the above-mentioned computational model. The optional function has limitations in the applicable range of biometeorological variables, such as T_a from -50 to 50 °C and v at 10 m height from 0.5 to 17 m/s [27–33].

A scientific question is what kind of thermal indicator will be proposed in the study. Before answering this question, the subject relevance of thermal environments, thermo-physiology, and textile science should be discussed and shown in Figure 1. Thermal environment focuses on the influences of T_a, v, air vapor pressure (VP_a), and T_{mrt}. Thermo-physiology investigates physiological reactions on thermal strains, such as thermoregulation, metabolic rate, heat beating rate, sweating mechanism, blood circulation, muscle shivering, microvascular contraction and relaxation. Textile science considers the functions of clothing insulation, vapor pressure resistance, clothing effective surface area, radiant reflect and transmittance. An interdisciplinary between thermal environment and thermo-physiology is regarded as a study of human thermal comfort and thermal strains. Most of previous rational and empirical thermal indicators focus only on the human thermal comfort and thermal stress. On perspective of textile engineering, the functions of clothing material are associated with environmental impacts as textile material engineering, and the adjustments of clothing design are associated with physiology as clothing ergonomics. Overall, all sufficient influences of thermally environmental impacts, reactions of thermo-physiology, and adaption performance of clothing against thermal conditions can be integrated as and considered in a new study filed as thermally environmental ergonomics. The modified PET (mPET) will be proposed as an indicator to serve this study field and to give an objective and comprehensive estimation of thermally environmental ergonomics.

The comparisons of the PET and the other thermal indicators are explained initially in the section—concepts and strategies of modification in the manuscript. The concepts to modify thermo-physiological model is proposed in the next paragraph. The solution including a bio-heat equation for the above-mentioned thermo-physiological model is immediately explained. Sequentially, the modification of clothing model and mechanisms of latent and radiant heat fluxes are clarified.

Furthermore, brief comparisons of the original PET and mPET are shown respectively according to thermo-environmental variables and clothing insulation in the manuscript.

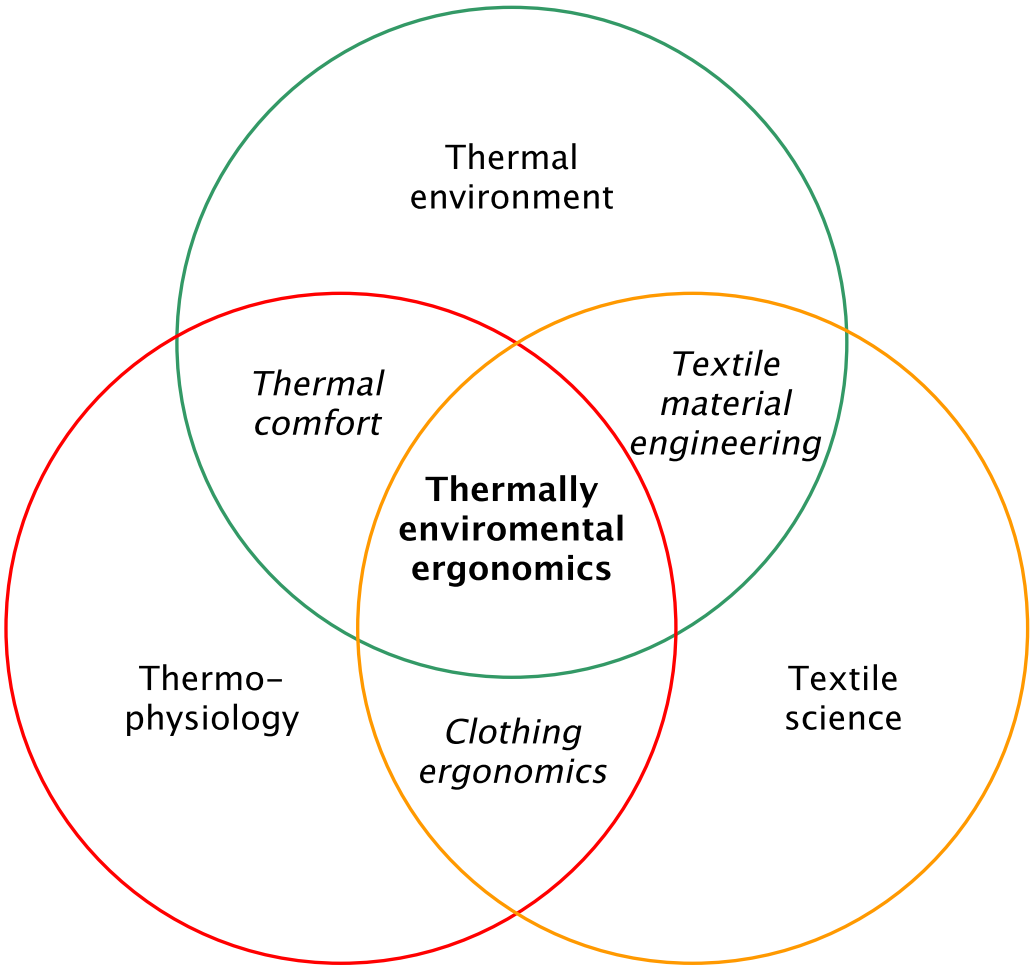

Figure 1. Concepts of thermally environmental ergonomics.

2. Concepts and Strategies of Modifications

The concepts and implements to modify PET in this study will be proposed in the followings. To develop an indicator of thermally environmental ergonomics, an effective and considerable clothing isolation mechanism is necessary to be additionally implemented in the whole computational model of mPET. Previously, PET has applied only one calculating node to represent the influence of clothing on human thermal strains. The calculating node is also one node in other previous thermal indices, such as PMV, SET*, and PT. However, the heat transfer approach of PET is different from above-mentioned thermal indices. There are two energy exchanging pathways from skin to environments in PET-model, but only one pathway in the other above-mentioned model (Figure 2). Beside of the 2-node body model, multiple-node body model has been also developed in 1966 [34] and UTCI is a more advanced thermal indicator to estimate thermal perception. Three different kinds of thermal indicators, which are PET, SET* and UTCI, have been briefly compared in Table 1 in advantages and disadvantages for thermally physiological factor, clothing adaption and thermally environmental factors.

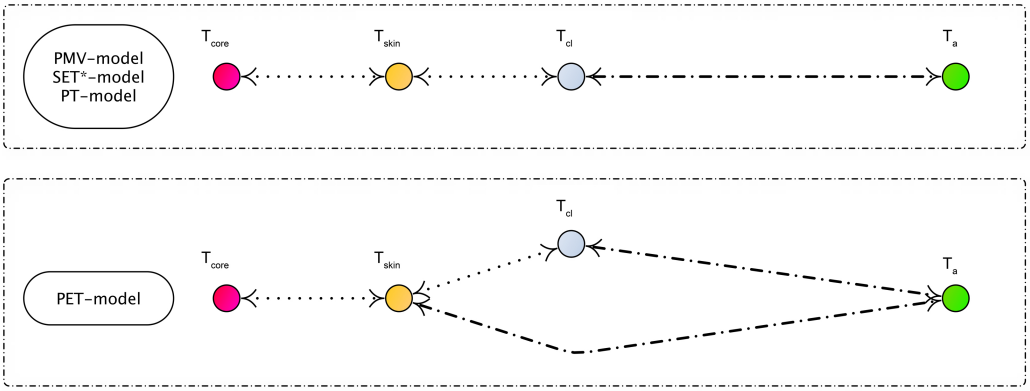

Figure 2. Comparison of sensible heat transfer between computational models of PMV, SET*, PT, and PET.

Table 1. Comparison between PET, SET* and UTCI.

	PET	SET*	UTCI
Physiological factors	2 nodes body model with variable parameters	2 nodes body model with standardized conditions	A regression function based on data and multiple-segment body model
Clothing adaption	Independently variable I_{cl}	I_{cl} adjusted by metabolic rate	Auto changing I_{cl} by T_a
Environmental factors	T_a, VP_a, T_{mrt}, v	T_a, VP_a, T_{mrt}, v	T_a, VP_a, T_{mrt}, v
Advantages	Good in T_a, T_{mrt}, v	Good in T_a, VP_a, I_{cl}	Good in T_a, VP_a
Disadvantages	Weak in VP_a, I_{cl}	Weak in T_{mrt}, v	Weak in v, T_{mrt} and no performance on I_{cl}

In original PET-model, there is only one skin temperature (T_{skin}) as one node which is impacted by both clothing temperature (T_{cl}) and ambient temperature (T_a) in sensible heat fluxes. Because of applying the above described energy flux approach, PET has also advantage in an estimation of radiant and wind impacts. However, the energy flux approaches of vapor pressure diffusion and sweating evaporation from skin are not clarified by the above-mentioned two energy pathways. In PET-model, the vapor pressure diffusion is considered to be zero energy flux in clothing covered pathway and as full statured skin vapor pressure diffusion in clothing uncovered pathway. On contrast, sweating rating is only dominated by gender difference and integrating influence of core and skin temperature and the whole sweating evaporation will not exceed the difference of skin saturated vapor pressure and actual air vapor pressure multiplying a coefficient representing clothing water vapor resistance. Therefore, PET has no impressive performance to realize the influence of changing environmental vapor pressure on human beings. The mPET-model is based on the previous stage of the PET-model to improve the above shortnesses in thermo-physiology, clothing isolation mechanism and the processes of the latent heat exchange.

2.1. Concepts to Modify Thermo-Physiological Model

Modification of PET is to solve not only the issues of PET but also further to improve PET as an indicator to serve thermally environmental ergonomics. Thus, initial implement of mPET for the purpose is to enhance the original single clothing calculating node to a multiple calculating nodes to represent a realistic clothing model with multi-layer garments [35]. Reasonably, different

exchanging heat fluxes could occur in a body segment due to different layers covered garments. Hence, a realistically computational model for mPET in two-layer garments to describe the sensible heat transfer in the approaches as a sample is displayed as the flow chart in the Figure 3a. The heat exchange between body and environments can be regard as energy fluxes transferring between the core temperature (T_{core}) and ambient temperature (T_a).

There are four different sensible heat transfers pathway in a mPET-model with a two-layer clothing model. The primary pathway of sensible heat transfer in the Figure 3a is from the core node directly through the body (muscle), the fat and the two skin nodes, then over the first clothing layer and the second clothing layer both with two calculating nodes (inner and outer nodes of the clothing layer), and finally to the ambient temperature, namely the actually environmentally thermal condition. The second pathway is from the core node through the two head nodes, fat node, and two skin nodes, and directly to the ambient temperature. The third pathway is also from the core node through two additional body segment nodes to represent partly remaining muscle segment, the fat node, the two skin nodes, then over one clothing layer with two calculating nodes, and finally until the ambient temperature. The fourth pathway is from the core node through the remaining body node which is covered by one layer clothing, then to the remaining body, then to fat node, and two skin nodes, and directly to the ambient temperature. Applying the four pathways can comprehensively and realistically describe the energy exchange between the body core and environments. Otherwise, the all heat transfers occur concurrently in all computational nodes. The latent and radiant heat transfers occur only above from the skin nodes to the environmental node. Overall, applying the thermo-physiological model with bio-heat equation [36,37] for each node can calculate all kind of heat transfers in various body segments.

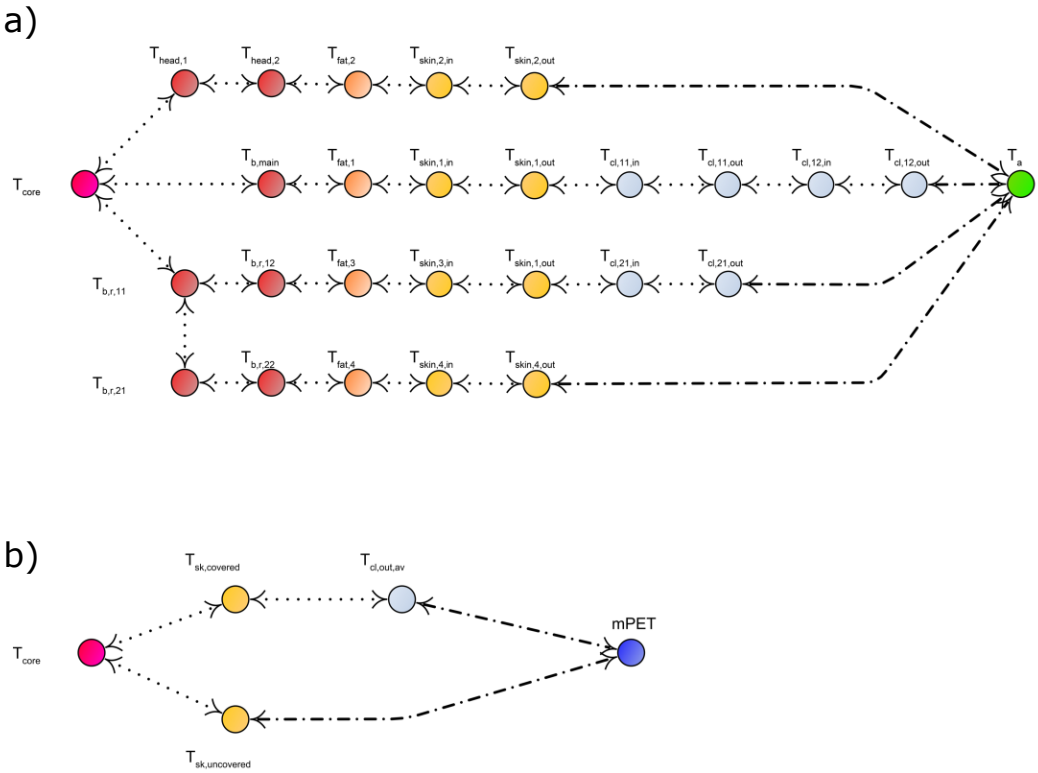

Figure 3. (**a**) The flow chart of sensible heat transfer of mPET-model with two-layer clothing and (**b**) calculation approach of mPET based on exchange fluxes.

While all heat fluxes in all segments, thermo-physiological variables, and textile parameters have been considered, a simplified three nodes model with the core node, the clothing covered and uncovered skin nodes is applied to carry out a corresponding equivalent temperature to heat fluxes

based on the human energy-balance equation (Figure 3b). This equivalent temperature is identified as modified physiologically equivalent temperature (mPET) as a revision of the PET. The human energy-balance equation for calculation of mPET is shown as the follows.

$$M_{act} + C_{act} + R_{act} + E_{d,act} + E_{sw,act} + Re_{act} + S_{act} = M_{ref} + C_{mPET} + R_{mPET} + E_{d,12hPa} + Re_{mPET} \quad (1)$$

where:

M_{act} is the actually metabolic rate (W/m^2);
C_{act} is the actually convective heat fluxes (W/m^2);
R_{act} is the actually radiant heat fluxes (W/m^2);
$E_{d,act}$ is the actual heat fluxes of the skin diffusion (W/m^2);
$E_{sw,act}$ is the actual heat fluxes of the sweating evaporation (W/m^2);
Re_{act} is the actually respiratory heat fluxes (W/m^2);
S_{act} is the actual storage heat fluxes inside body (W/m^2);
M_{ref} is the metabolic rate of the reference (W/m^2);
C_{mPET} is the convective heat fluxes based on the value of mPET (W/m^2);
$E_{d,12hPa}$ is the heat fluxes of the skin diffusion corresponded to 12 hPa vapor pressure (W/m^2);
R_{mPET} is the radiant heat fluxes based on the value of mPET (W/m^2);
Re_{mPET} is the respiratory heat fluxes based on the value of mPET (W/m^2).

The Equation (1) is applied in the process of the assessment referring to PET's standard conditions which have been mentioned in the manuscript of the Chen and Matzarakis [38]. The mPET can realize the thermo-physiological strains under the actual thermal conditions and based on the rational method to convert the integrating energy fluxes to an appropriate equivalent temperature.

2.2. Bio-Heat Equation and Solution for Thermo-Physiological Model

The energy transfer between the thermo-physiological nodes of mPET-model is not a simple conductive heat transmission but includes heat exchanges of the blood circulation system and other physiological mechanisms. Pennes [36] has proposed a bio-heat equation based on a medal experiment to describe the heat transfer for a tissue inside a human being's body. The bio-heat equation is presented as the following.

$$\kappa_{ti}\left(\frac{\partial^2 T_{ti}}{\partial r^2} + \frac{\omega}{r}\frac{\partial T_{ti}}{\partial r}\right) + q_m + \rho_{bl} w_{bl} c_{bl}\left(T_{bl,a} - T_{ti}\right) = \rho_{ti} c_{ti}\frac{\partial T_{ti}}{\partial t} \quad (2)$$

where:

κ_{ti} is the tissue conductivity (W/(m^3·K));
T_{ti} is the tissue temperature (°C);
r is the radius of tissue (m);
q_m is the metabolic rate (W/m^3);
ρ_{bl} is the density of blood (kg/m^3);
ω is the geometry factor of the tissue $(-)$;
w_{bl} is the blood perfusion rate (1/s);
c_{bl} is the heat capacity of blood (J/(kg·K));
$T_{bl,a}$ is the arterial blood temperature (°C);
ρ_{ti} is the density of the tissue (kg/m^3);
c_{ti} is the heat capacity of the tissue (J/(kg·K));
t is the time (s).

One bio-heat equation can only present one computational node of the thermo-physiological model. Thus, for a whole body with 2-layer clothing model of mPET in the top of Figure 3, 20 bio-heat equations are applied to simulate the heat transfer inside the human body. Additionally, one more equation should be appended to describe the heat transfer in the blood circulation system. Finally, for a whole body model with 2-layer clothing model, 21 heat transfer equations should be solved meanwhile at the same one time step. To solve the multiple equations at the same one time step, Fiala et al. [16,17] have introduced a matrix form based on the Crank-Nicolson's scheme [39]. The original Crank-Nicolson's method is applied to solve parabolic partial differential equations, which is applied to describe simple sensible heat transfer fluxes between materials in a mathematic form. Fiala et al. [16,17] have developed an approach to integrate the heat transfer of the blood circulation system inside body and the parabolic partial differential equations for all tissues in a matrix form. To apply the approach, the body temperature profile, including the core temperature and all tissue temperature, and an effective temperature profile of inner clothing and environmentally thermal conditions as initial boundary conditions are required. Finally, a semi-steady condition of the thermo-physiology can be deduced by the mPET-model and the Fiala's approach involved by the environmentally thermal conditions. The all kinds of the energy fluxes can be also generated and be afforded to calculate the mPET (Figure 3).

2.3. Modifications of Clothing Model

The clothing model of mPET-model has been enhanced to a multiple-layer clothing model varied by the clothing insulation. It is also the most essential modification of the mPET-model. For multiple-layer clothing model, the clothing covered surface areas of different layer of clothing is necessary to be identified aiming to calculate the whole energy gain or loss between the body and environment. Table 2 shows that the various clothing covered areas by multiple clothing layer in different clothing insulation from 0.3 to 2.5 clo. For instance, while the total clothing insulation is from 0.3 to 0.6 clo, 62% body surface area is covered by single layer clothing and 38% body surface area is uncovered. The specific one scheme is the multiple-layer clothing covered by triple layer, double layer, single layer, and a cap, while the total clothing insulation is from 2.0 to 2.5 clo. The cap is also a single layer clothing but covers the head division of the mPET-model. The cap covered surface area is different from the single layer covered surface area. The single layer covered surface in the clothing model represents remaining body division covered by single layer clothing. Overall, clothing covered and uncovered surface areas of the body cylinder identify the ratio of the body surface areas of the different heat fluxes transfer [38].

Table 2. Clothing covered and uncovered surface area.

Clothing Insulation (clo)	Single Layer	Double Layer	Triple Layer	Cap	Uncovered
0.3~0.6	62%	-	-	-	38%
0.6~0.9	36%	45%	-	-	19%
0.9~1.2	42%	45%	-	-	13%
1.2~1.6	30%	22%	35%	-	13%
1.6~2.0	26%	22%	45%	-	7%
2.0~2.5	12%	25%	55%	5%	3%

The energy exchanging fluxes over the clothing covered section are affected by clothing insulation and clothing water vapor resistance. Figure 4 illustrates all kinds of the energy exchanging channels in mPET clothing model with double-layer clothing including sensible and latent heat transfers from the outer skin to ambient environment and radiant heat transfer from outer clothing or skin. The thermo-regulatary model of the mPET does not directly deduce the actual skin vapor pressure. However, for a realistic simulation of the heat transfer between human beings and thermal environments, latent heat transfer between the outer skin and environment is an essential impact.

In the mPET-model, the outer skin temperature profile is applied to calculate the saturated vapor pressure of the skin as boundary conditions. Applying skin saturated vapor pressure and actual air vapor pressure as boundary conditions can appraise the actual skin vapor pressure and actual clothing vapor pressure profiles with the sweating mechanism and restriction of the clothing and skin water vapor pressure resistance. Another important issue is the condensation of the water vapor in between the clothing. These phenomena can involve the entire heat transfer of the latent and sensible exchange [35]. In mPET clothing model with double-layer garments, the involvement of the water vapor condensation inside of clothing is considered to be the interaction of pair nodes in clothing temperature and vapor pressure ($T_{cl,11,in}$ and $VP_{cl,11,in}$; $T_{cl,12,in}$ and $VP_{cl,12,in}$; $T_{cl,21,in}$ and $VP_{cl,21,in}$ in Figure 4). The modification of mPET clothing model provides a more realistic calculation to describe the heat transfer in multiple-layer garments and potential to be enhanced to evaluate the effectiveness of newly developed clothing type or textile materials on thermally environmental ergonomics.

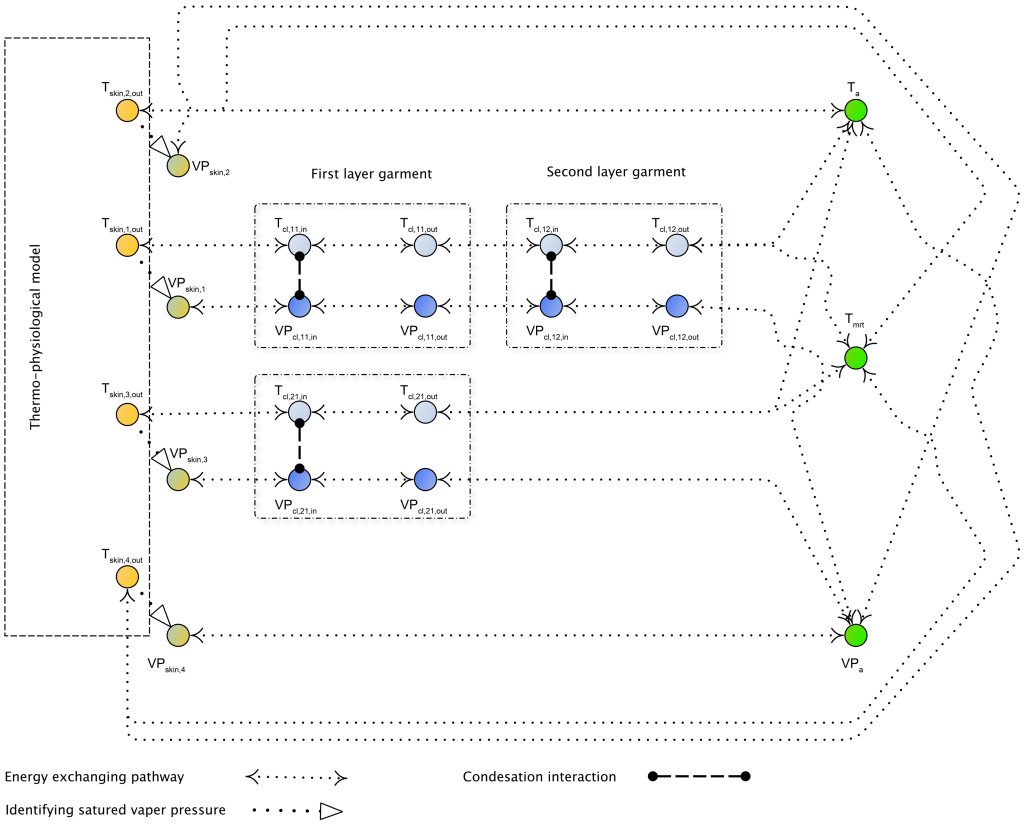

Figure 4. The flow chart of all energy fluxes of the double-layer clothing model.

2.4. *Mechanisms of Latent Fluxes*

The mechanism of the latent heat flux is modified in mPET-model due to the changing of the vapor pressure transmission of clothing model and the sweating evaporation process of the thermo-physiological model of the mPET. The fundamental theory of the radiant heat flux of the mPET-model is not verified, but the radiant heat flux is modified because of changing of the outer clothing and skin temperature profile.

The original equation for calculating latent fluxes of the PET-model is derived by the following.

$$E_{latent} = f_{gender} \times \frac{\lambda_{H2O}}{A_{sk}} \frac{dm_{sw}}{dt} + (1 - ratio_{sk,moist}) \times \frac{VP_{sk,sat} - VP_{sk}}{R_{e,sk}} \quad \left(W/m^2\right) \tag{3}$$

$$f_{gender} \times \frac{\lambda_{H2O}}{A_{sk}} \frac{dm_{sw}}{dt} \leq \frac{(VP_{sk,sat} - VP_{air})}{f_{e,cl} \times R_{e,sk}} \quad \left(W/m^2\right) \tag{4}$$

$$ratio_{sk,moist} = \frac{f_{gender} \times \frac{\lambda_{H2O}}{A_{sk}} \frac{dm_{sw}}{dt}}{\frac{(VP_{sk,sat} - VP_{air})}{f_{e,cl} \times R_{e,sk}}} \tag{5}$$

$$\frac{dm_{sw}}{A_{sk}dt} = \frac{0.3049 \times ((0.1 \times T_{sk} + 0.9 \times T_{core}) - 36.6)}{3600} \quad \left(kg/m^2 s\right) \tag{6}$$

where:

E_{latent} is the latent heat fluxes (W/m^3);
f_{gender} is the gender factor of sweating rate $(-)$;
λ_{H2O} is the evaporative energy of the liquid water per gram (W/kg);
A_{sk} is the skin surface area (m^3);
$\frac{dm_{sw}}{dt}$ is the sweating rate (kg/s);
$ratio_{sk,moist}$ is the ratio of skin moisture $(-)$;
$VP_{sk,sat}$ is the saturated skin vapor pressure (hPa);
VP_{air} is the actual air vapor pressure (hPa);
$R_{e,sk}$ is the skin resistance of the vapor pressure (hPa·m^2/W);
$f_{e,cl}$ is the clothing factor of vapor pressure resistance in the PET-model $(-)$.

The original skin diffusion heat fluxes in PET-model has only quantified the heat fluxes in clothing uncovered component of the body model. The skin diffusion over clothing covered segment is regarded as no transfer heat fluxes. The sweating evaporative heat loss in the original PET-model has been considered by the clothing resistance of vapor pressure with an additional factor to quantify the maximum sweating evaporative heat loss in clothing covered segment (Equation (4)). The actual sweating generation is dominated by a function derived by the core and skin temperatures (Equation (6)).

Improvements of the latent heat fluxes transfer in mPET-model are according to an actual skin vapor pressure which is based on the actual sweating mechanism, air vapor pressure, skin vapor pressure resistance, and clothing vapor pressure resistance.

A modified equation based on the latent heat fluxes balance as Equation (7) is applied to calculate the actual skin vapor pressure and actual latent heat fluxes for the mPET-model to replace Equation (3) in the original PET-model. The sweating generating equation (Equation (6)) is also replaced by Equation (8).

$$E_{latent} = \frac{(VP_{sk} - VP_{air})}{R_{e,cl} \quad or \quad R_{e,sk}} = f_{gender} \times \frac{\lambda_{H2O}}{A_{sk}} \frac{dm_{sw}}{dt} + \frac{VP_{sk,sat} - VP_{sk}}{R_{e,sk}} \quad \left(W/m^2\right) \tag{7}$$

$$\frac{dm_{sw}}{A_{sk}dt} = \frac{0.001}{60} \left[0.43 \tanh\left(0.59\Delta T_{sk} - 0.19\right) + 0.65\right] \Delta T_{sk} + \left[3.06 \tanh\left(1.98\Delta T_{core} - 1.03\right) + 3.44\right] \Delta T_{core} \quad \left(kg/m^2 s\right) \tag{8}$$

where:

E_{latent} is the latent heat fluxes (W/m^3);
VP_{sk} is the actual skin vapor pressure (hPa);
VP_{air} is the actual air vapor pressure (hPa);
$R_{e,cl}$ is the clothing resistance of the vapor pressure (hPa·m^2/W);
$R_{e,sk}$ is the skin resistance of the vapor pressure (hPa·m^2/W);

f_{gender} is the gender factor of sweating rate $(-)$;
λ_{H2O} is the evaporative energy of the liquid water per gram (W/kg);
A_{sk} is the skin surface area (m^3);
$\frac{dm_{sw}}{dt}$ is the sweating rate (kg/s);
$VP_{sk,sat}$ is the saturated skin vapor pressure (hPa).

Applying the above-mentioned modified scheme could lead to a more realistically and reasonably actual latent heat flux to evaluated the influence of evaporation of skin vapor pressure and sweating over the clothing garments and the outer skin.

3. Comparison of PETs

Comparison of the original and modified PETs is categorized by thermally environmental variables in T_a, v, RH, and T_{mrt} and clothing insulation (Icl). The sensitivity tests have been carried out in these conditions, which are T_a from -20 to 40 °C, v from 0.1 to 5 m/s, RH from 10 to 90%, T_{mrt} from T_a to $T_a + 20$ °C, and Icl from 0.6 to 1.5 clo. To illustrate the results of the sensitivity tests once in multiple variables is incomprehensible. Therefore, the comparisons of PET and mPET are shown with the changing of v, RH, T_{mrt}, and Icl in the different T_a conditions. A reference condition, which are v in 0.1 m/s, RH in 50%, T_{mrt} equal to T_a , and Icl respectively in 0.9 clo for PET and in default for mPET, is applied for non-aligned variables as input conditions. The comparisons of PET and mPET are shown respectively in subsections of thermally environmental variables and clothing adaption.

3.1. Sensitivity Tests of the Thermally Environmental Variables

In the section, the comparison of PETs is shown by the involvement of T_a initially. Then the comparisons of PET and mPET are respectively shown in the v, RH, and T_{mrt} according to different T_a. This is because the variance of the other thermal environmental variables highly relates to the changing of the T_a.

Figure 5 illustrates the sensitivity test of T_a. The PET varies according to the changing of T_a as a linear-changing function. Otherwise, while T_a is -20 °C, the value of PET is lower than -20 °C. On contrast, the value of PET is higher than 40 °C, while T_a is 40 °C. The mPET varies nonlinearly according to the changing of T_a. The value of the mPET is equal to the PET, while the T_a is 20 °C which is regard as a reference of standard condition for thermal comfort zone of the human beings. In the neutrally thermal conditions, mPET varies itself mellowly according the decreasing or increasing of the T_a. Out of the range of the neutrally thermal conditions, mPET increases itself in a similar rate as PET according to the changing of T_a. Concurrently, the mPET slope of the T_a is relatively smaller than the PET slop of the T_a in the cold stress. Overall, mPET has a less range of the variation than PET according to the changing of T_a. Figure 6 illustrates the sensitivity test of v respectively in each 5 °C of T_a from -20 to 40 °C. The mPET gradient of the v is similar to the PET gradient of the v. However, the value of mPET is significant different from PET in the cold stress because of the influence of T_a. While T_a is higher than 35 °C, the value of the mPET is slightly lower than PET. This is because the evaporation of the sweat performs effectively in the mPET-model and the RH is given as 50% in the test. The comparison of the humidity sensitivity between mPET and PET is shown in the Figure 7. The changing of RH involves mPET more significant than PET, while the T_a is higher than 25 °C. The increasing RH lead to an ascending mPET in the warm conditions. Meanwhile, mPET has the similar performance due to the involvement of RH as PET in the cold conditions. The PET varies itself so tiny almost as no difference according to the changing of RH whatever in warm or cold stress. This result shows that mPET can realize the influence of humidity on the thermal strain of the human beings in hot conditions. PET is quiet sensitive to the changing of T_{mrt}, hence, PET could reflect the influence of the radiant fluxes on subjects effectively specifically in outdoor. The mPET has different performance on the impact of the radiant fluxes from the PET (Figure 8). In the cold conditions, mPET is involved by also the impact of T_a and higher than PET, but the contributions of the T_{mrt} is similar to

mPET and PET. In hot conditions, the mPET slop of the T_{mrt} is smaller than the slop PET of the T_{mrt}. This could be regarded as that the changing of the mPET due to the T_{mrt} is slighter than PET.

In summary, the mPET can be regarded as a more comprehensive and effective thermal index to evaluate the all thermally environmental impacts than the original PET. The thermo-physiological mechanism and clothing isolation model contribute to the major difference between the mPET and PET, which involved by estimation of the impact of T_a. The other thermally environmental impacts on the thermal indices are highly involved also by T_a. In hot conditions, mPET is less sensitive to T_{mrt} but more sensitive to RH than PET. About the influence of v between mPET and PET is slightly different. Overall, mPET can bring a realistic evaluation of the thermally environmental variables close to the thermal stress on the human beings.

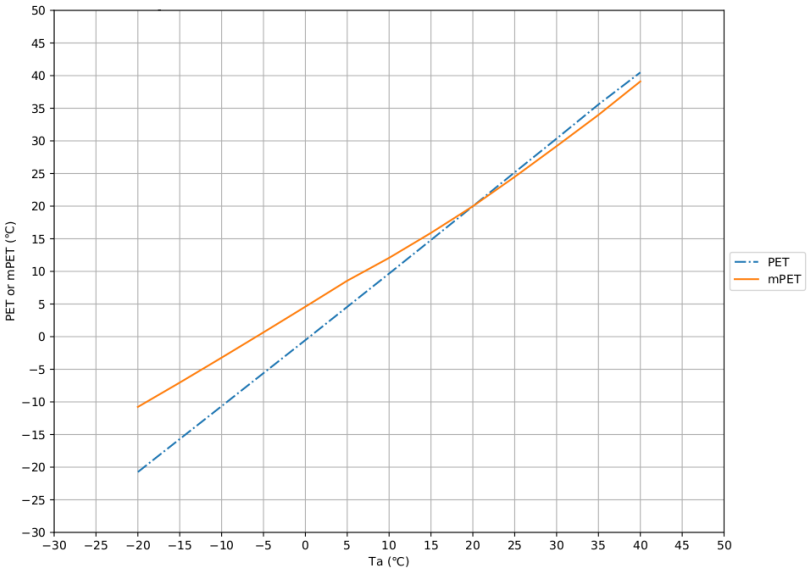

Figure 5. The comparison of PET and mPET in different T_a.

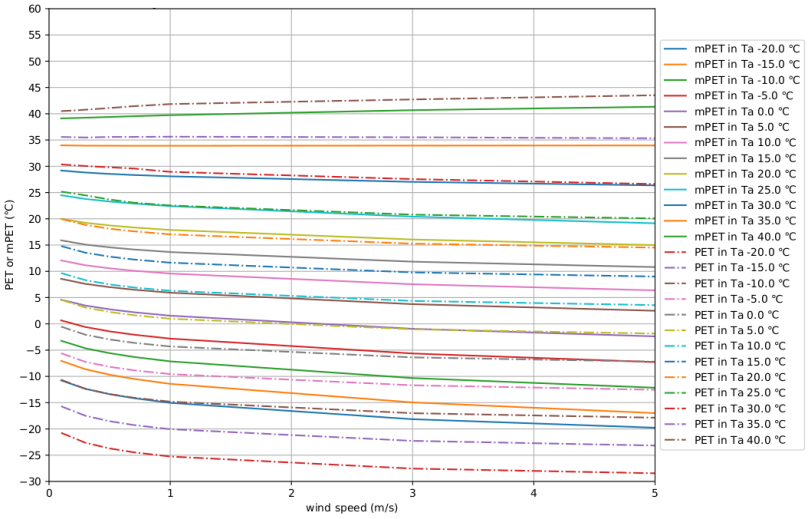

Figure 6. The comparison of PET and mPET in different T_a and v.

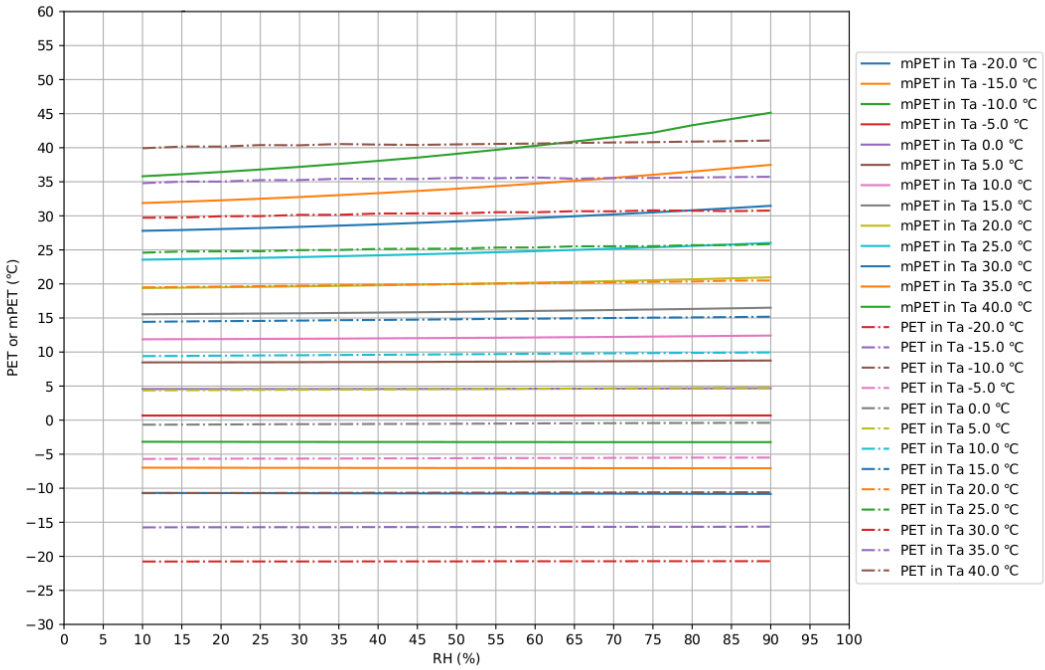

Figure 7. The comparison of PET and mPET in different T_a and RH.

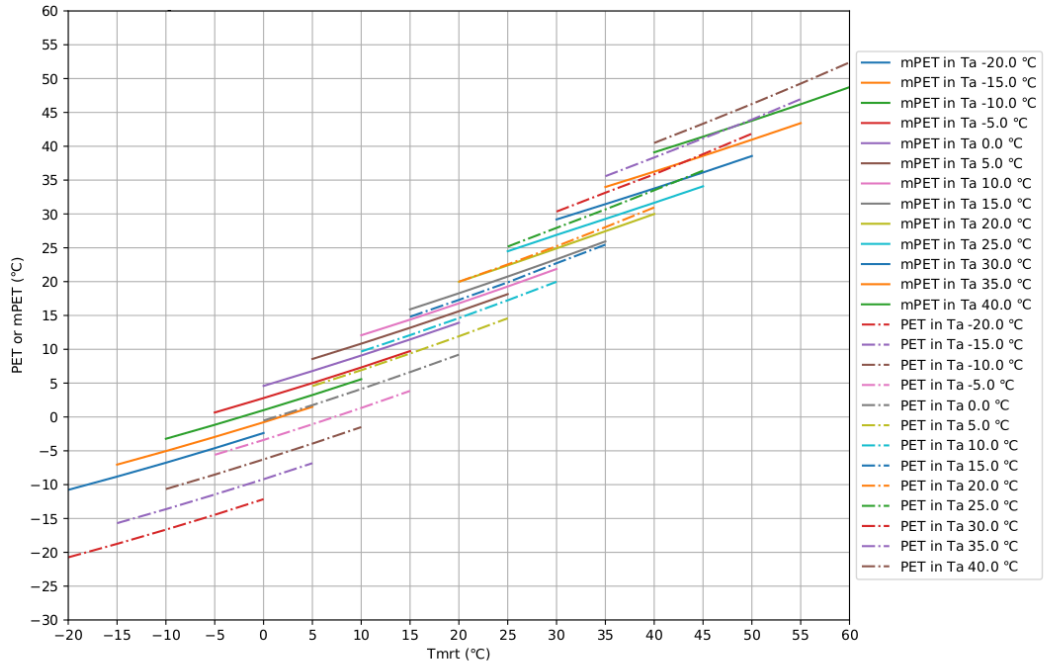

Figure 8. The comparison of PET and mPET in different T_a and T_{mrt}.

3.2. Clothing Influences

Applying clothing to prevent the impacts of the thermal environment has been in long history. Thus, a thermal index should also consider the adjustment of the thermal strains caused by the different Icl. As the Figure 9 shown, the PET has almost no performance on the variation of Icl. Meanwhile, the mPET has significant different performance on the variation of Icl from the PET. An increasing tendency of mPET is involved by the changing of the Icl in the cold conditions. On the contrast, mPET has no significant different tendency from PET, while T_a is greater than 35 °C. The result considers

that the clothing mechanisms of the mPET-model could effectively realize the influence of different clothing behaviors on the thermal strains.

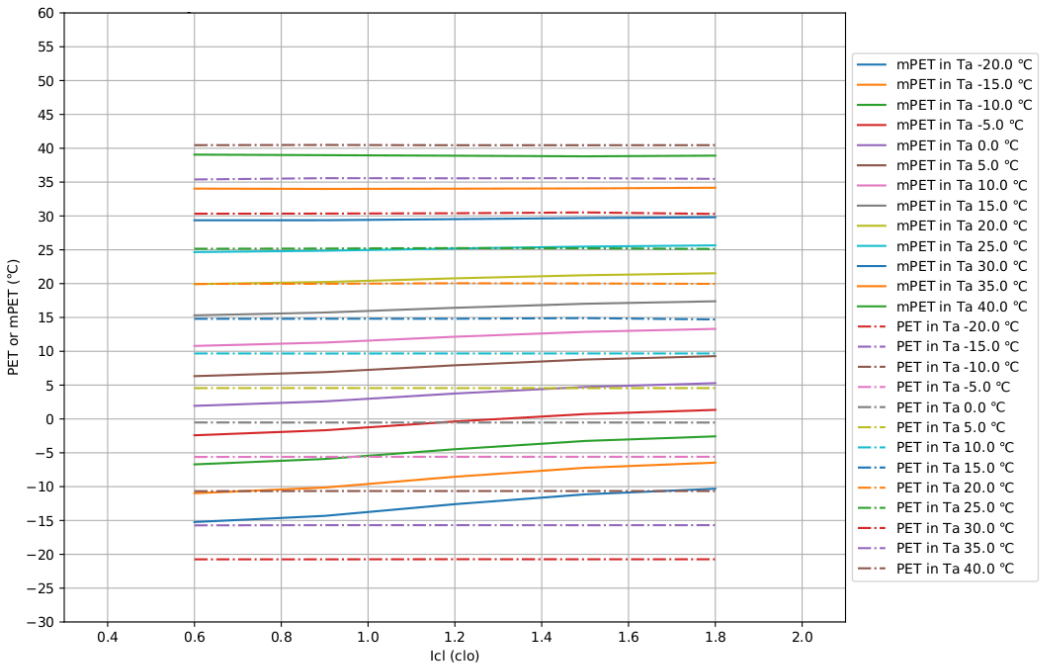

Figure 9. The comparison of PET and mPET in different T_a and Icl.

4. Discussion

The mPET-model is significantly different from original PET-model. The original PET has been evident as a widely applicable thermal index compared to the PMV [10,11], SET* [12–14] and PT [19,20]. These above-mentioned thermal indices are all based on a two-nodes thermo-physiological model and the principle of the human energy balance. A two-nodes thermo-physiological model [1,2,10–14] is consisted of a shell layer and a core segment to represent the human body. The entire human body is regarded as a homogeneous cylinder by the two-nodes thermo-physiological model. This kind of the thermo-physiological model has mostly considered only heat flux transfer according to the blood circulation and neglected the conductive heat flux transfer between the shell and core layers. Therefore, some thermoregulary reactions of human beings, such as vasoconstriction and shivering, are not entirely considered by the two-nodes thermo-physiological model. To realize the vasoconstriction and vasodilation, a multiple-segments body model is necessary to be applied as a thermoregulation model to describe not only the heat transfer of blood circulation but also the conductive heat transfer between the segments of the subject's body as a non-homogeneous and dynamic energy-balance state. Stowijk and Hardy [34] have initially proposed a 3 segment body model with head, trunk and external part to represent the heat transfer pathway inside the body. This model had solved parts of the issue about the heat transfer inside the human beings' body. Moreover, Huizenga, et al. [40], Tanabe et al. [41], and Fiala, et al. [16–18], have respectively three different thermo-physiological models to realize the heat transfer inside human beings' body. The model of Huizenga, et al. [40] is called the Berkeley Comfort Model which is an improved model from Stowijk and Hardy [34]. The Berkeley Comfort Model has applied the Icl as a parameter in the model and also Equivalent Homogenous Temperature [42] for each segment of the entire body but not estimation of subject's thermal perception. Tanabe et al. [41] proposed a thermo-physiological model with 65 segments to simulate the conductive heat transfer and energy exchanging with blood circulation between each segment. This model applies an effective temperature based on the thermo-physiological variables to represent the human thermal perception. Fiala, et al. [16–18] have developed another complicated

thermo-physiological model with 304 segments to represent the heat flux exchanging inside the human being's body. Fiala's approach has benefited from an effective calculation of thermo-physiological changes of all segments in the same time step. Hence, the original Fiala's model requires a lot of the computational time and can generate a time-depending model to realize the thermal perception. To save the computational time, the clothing model has been parameterized from a multiple-layer clothing model to a total clothing insulation [43]. Finally, Fiala's model applies a 6th order regression function based on the European and Russian data base in certain limited human biometeorological conditions to calculate an effective temperature for indication of the thermal perception [15].

The mPET is further different from the most above-mentioned thermal indicators and has given a comprehensive and effective estimation of thermal perception in a balance of considering thermo-physiological activity, clothing influences and environmental impacts. Additionally, the computational time of the mPET has been also controlled in an acceptable length. Overall, the mPET-model has only up to the maximum 5 segments with 25 elements and integrates the clothing influences and thermoregulary performance in a meaningful discriminate mode. It could save either computational time or also integrate a realistic clothing model but not a parameterized variable into the entire model. The mPET can performance the tissue temperature of each element and the blood temperature inside body. On the surface of the body model, the skin wettedness, moisture ratio of the skin, skin vapor pressure and sweating rate have been used to realize the latent heat flux exchanging. Based on the above-mentioned thermo-physiological variables. the mPET-model can provide an appropriate approach to estimate the energy exchanging between the human body and environments in a certain time step and consider the impacts of clothing resistance in sensible and latent heat fluxes. In some previous studies have proofed that mPET could estimate well the influence of humid factors on human beings [38,44]. Finally, the mPET-model applies a human-body energy-balance equation to give an equivalent temperature. The mPET-model provides a rational and further modifiable computational approach to estimate the thermal perception.

5. Conclusions

This article delivers the target study fields, the thermo-regulatory model based on a multiple-segment physiological model, the multi-layer clothing model associate to the multiple-segments physiological model, and the evaluation function for equivalent temperature based on a semi-energy-equilibrium state of the mPET-model. The ordinary thermal indices focus on the impacts of the thermally environmental variables on the human beings. However, the mPET has been purposed as a further ubiquitous index to investigate the thermally environmental ergonomics, including evaluation of the environmental impacts, physiological changing, and ordinary textile effectiveness on thermal perception. The mPET-model has further potentiality to implement the clothing model of modern specific textile materials or traditional costumes in various places and evaluates the effectiveness of these clothing behaviors.

The thermo-regulatory mechanism and the multiple-segment physiological model of the mPET-model is clearly explained in the study. The multiple-segment physiological model in the mPET-model collocates the multiple-layer clothing model to replicate the phenomenon of vasoconstriction and vasodilation, the effectiveness of the clothing insulation and clothing vapor resistance, and a realistic blood and body heat transfer simulation. Thus, a mPET is supposed to give a more realistic evaluation of the thermal perception. The sensitivity test of the biometeorological variables and clothing impact proves that the modified PET has better performance on the humidity and clothing insulation than the original PET.

In summary, the fundamental mechanisms of the mPET-model and the calculating approaches of the mPET have been clarified in the article, to be extended to be an appropriate indicator to the thermally environmental ergonomics.

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